REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)

2. REPORT DATE
September 30, 2003

3. REPORT TYPE AND DATES COVERED
Final Technical, 25/07/02 – 30/06/03

4. TITLE AND SUBTITLE
The Extratropical Transition of Tropical Cyclones

5. FUNDING NUMBERS
N00014-02-1-0937

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unlimited

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The extratropical transition (ET) of tropical cyclones can sometimes result in rapid changes in the structure and intensity of the tropical cyclone. In particular, the second stage of ET can result in very different results from complete dissipation to rapid intensification into an intense midlatitude cyclone. Whether the tropical cyclone dissipates or reintensifies appears to be strongly dependent on the details of the midlatitude circulation. At the heart of the forecast problem is a lack of knowledge of the fundamental physical changes occurring during ET.

Results are presented that show that the details of the midlatitude circulation are probably less important than the basic midlatitude structure for reintensification. Simulations presented here show that variations in the strength of the midlatitude upper-level trough have little impact on the subsequent reintensification of the tropical cyclone. Rather, it is more likely the energy of the background environmental state, and the phasing between the trough and TC that ultimately determine the intensity to which the cyclone can reintensify.

14. SUBJECT TERMS
tropical cyclone, structure, intensity, numerical modeling, landfall, extratropical transition

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	None

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-1
298-102

20031015 030

THE EXTRATROPICAL TRANSITION OF TROPICAL CYCLONES

Final Report

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N00014-02-1-0937
1 JUL 2002 – 30 JUN 2003

Overview of the problem:

The tropical environment in which a tropical cyclone forms and intensifies may be fairly benign. The relatively small latitudinal gradients in air and sea temperature, and small values of vertical wind shear in the tropics will enable the tropical cyclone to intensify near its theoretical maximum potential intensity. However, as the tropical cyclone moves poleward, it begins to encounter a midlatitude environment, which includes lower sea-surface temperatures, horizontal air temperature gradients, and strong upper-level westerly winds. As the tropical cyclone moves into this hostile environment, its structure is substantially changed via an interaction called extratropical transition. This interaction with the midlatitude environment may completely destroy the tropical cyclone structure, or the transformed tropical cyclone may re-intensify as a midlatitude cyclone, with additional sources of moisture due to its tropical origins. In the western North Pacific alone, on average fifteen tropical cyclones transform into extratropical storms every year. These storms can produce high winds, seas, and copious amounts of rainfall, and because of their rapid forward motion, they are difficult to forecast accurately. They are a threat not only to transiting Navy ships, but also to coastal facilities on the west coasts of the U. S., Canada, and Europe, and to Australia and New Zealand where they are have caused severe wind and flooding events (Foley and Hanstrum 1994). There are three primary ways to obtain better forecasts: improve the models; improve the data; and achieve better understanding of how the tropical cyclone structure changes. Although research in all three is needed, the lattermost approach is particularly essential to improve forecasts in the next several years. At the heart of the forecast problem lies a lack of understanding of how the tropical cyclone structure responds to changes in the large-scale flow. This is the problem addressed by this proposed research. In addition, by using a forecast model as a tool to gain better understanding of the extratropical transition problem, a potential side product of the research is improvements in forecast model performance down the road.

The physical processes that produce changes in tropical cyclone structure and intensity during extratropical transition are complicated, particularly because several environmental factors have

been identified that may play important roles. These factors include the colder, drier midlatitude air, the lower sea-surface temperatures, the vertical wind shear associated with increasing midlatitude westerlies, strong low-level air temperature gradients, and the strength and size of midlatitude upper-level troughs (e.g., Klein et al. 2002; Ritchie and Elsberry 2001; 2003). Ritchie and Elsberry (2001) studied the structural changes of a simulated tropical cyclone as it moved poleward and interacted with a midlatitude environment. This study indicated that both the low-level temperature structure of the atmosphere and the large-scale vertical wind structure were extremely important to produce the irreversible changes that occurred during transformation in their simulations. Ritchie and Elsberry (2001) simulated the final transformed structure of the tropical cyclone just prior to when possible re-intensification would occur as part of an interaction with an upper-level trough. They discovered that whereas the upper-troposphere warm core of the transformed tropical cyclone was drastically altered, a concentrated cyclonic wind structure below 500 mb was maintained. This was attributed to the development of an enhanced low-level warm core of the storm that could continue to support low-level cyclonic winds beyond when spin-down processes would probably have eliminated any circulation. In addition, maximum ascent was simulated in the northern quadrant of the tropical cyclone although no eyewall structure remained and the southwest quadrant was completely clear of precipitation. One major question that remained from this study was to understand how this transformed tropical cyclone structure could interact with an upper-level, midlatitude trough to produce a rapidly intensifying extratropical storm.

Objectives:

The main objective of this study was to investigate the interaction between a tropical cyclone and a realistic midlatitude environment incorporating an upper-level trough. In this study the results of Ritchie and Elsberry (2001) were extended to include upper-level features that have been identified in numerous studies as important to the re-intensification stage of extratropical transition (e.g., Harr and Elsberry 2000; Harr et al. 2000). In particular, the interaction between a tropical cyclone and a midlatitude upper-level trough was simulated (e.g., Figure 1) and the results were compared with, and validated against the observational studies of Harr and collaborators. In addition, physical changes in the core of the tropical cyclone were resolved by the model data and the physical processes that lead to differences between deeply intensifying, moderately intensifying, and non-intensifying extratropical storms were investigated.

Methodology:

Based on vertical profiles of the azimuthally averaged winds from 30 cases, a basic environment was specified to represent the baroclinic zone during extratropical transition. An upper-level potential vorticity perturbation is then added to the environment to represent the upper-level trough. The strength of the trough was varied from weak (15 m/s wind perturbation) through strong (35 m/s wind perturbation). To simulate the interaction between a tropical cyclone and midlatitude trough, a tropical cyclone vortex was inserted into the environment 15°S and 25°E of the upper-level trough. The tropical cyclone had been spun up for 48 h in a quiescent environment until the cloud fields were fully developed and the surface pressure was steady. An advective flow of 5 m/s from the

southwest was added to the tropical cyclone circulation so that the initial motion was 5 m/s to the northeast.

Simulations were performed using the U.S. Navy Coupled Ocean-Atmosphere Model Prediction System (COAMPS) (Hodur 1997). An ocean prediction model was not included in this study. The primitive equations were solved on a Lambert conformal grid, with a terrain-following - coordinate in the vertical. The model had 36 layers from sigma = 0 to 1, with the vertical boundaries at 30 km and the ocean surface. The model domain was configured with a coarse and fine mesh with grid spacing of 81 km and 27 km, respectively. The coarse domain of 87 x 93 grid points was large enough to allow an adequate representation of the idealized baroclinic zone during the integration. The fine domain of 124 x 190 grid points captured the primary structural modifications of the tropical cyclone as it interacted with the baroclinic environment. Simulations were run out to 144-h and included three trough-only cases where the strength of the upper-level trough was varied from weak, to moderate, to strong, and three comparable trough-with-TC cases.

Summary of Results:

Six simulations were used to describe the development processes of an extratropical cyclone during the reintensification stage of ET. Since the objective was to elucidate the role of the strength of the midlatitude upper-level trough, the first set of three simulations (the controls) examined the extratropical cyclogenesis associated with upper-level troughs that were characterized as weak (15 m/s perturbation), moderate (25 m/s perturbation), and strong (35 m/s perturbation). The second set of three simulations, the interactions of a tropical cyclone with each of the three upper-level troughs, were compared with the control simulations to illustrate the contributions to the extratropical transition of the tropical cyclone.

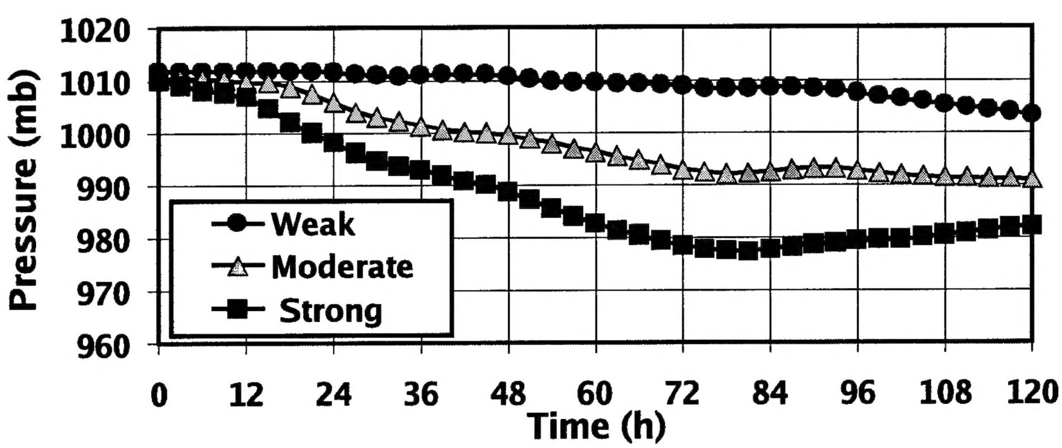

Figure 1. Time series of the minimum surface pressure for each of the three control simulations of a developing upper-level trough without a tropical cyclone present.

As expected, when no tropical cyclone was included in the simulation, the deepest surface cyclone (977 mb) developed in association with the strongest midlatitude trough and the weakest surface cyclone (1003 mb) developed in association with the weakest midlatitude trough (Figure

1). This expected trend is consistent with the hypothesis of Klein et al. (2002) that the development of the surface cyclone as part of the re-intensification stage of the ET of a tropical cyclone should depend strongly on the characteristics of the midlatitude circulation into which the TC is moving. In all three cases, the low tilted northwestward with height during intensification, and the rainfall pattern and eventual occlusion were representative of classic extratropical cyclone development (Figure 2).

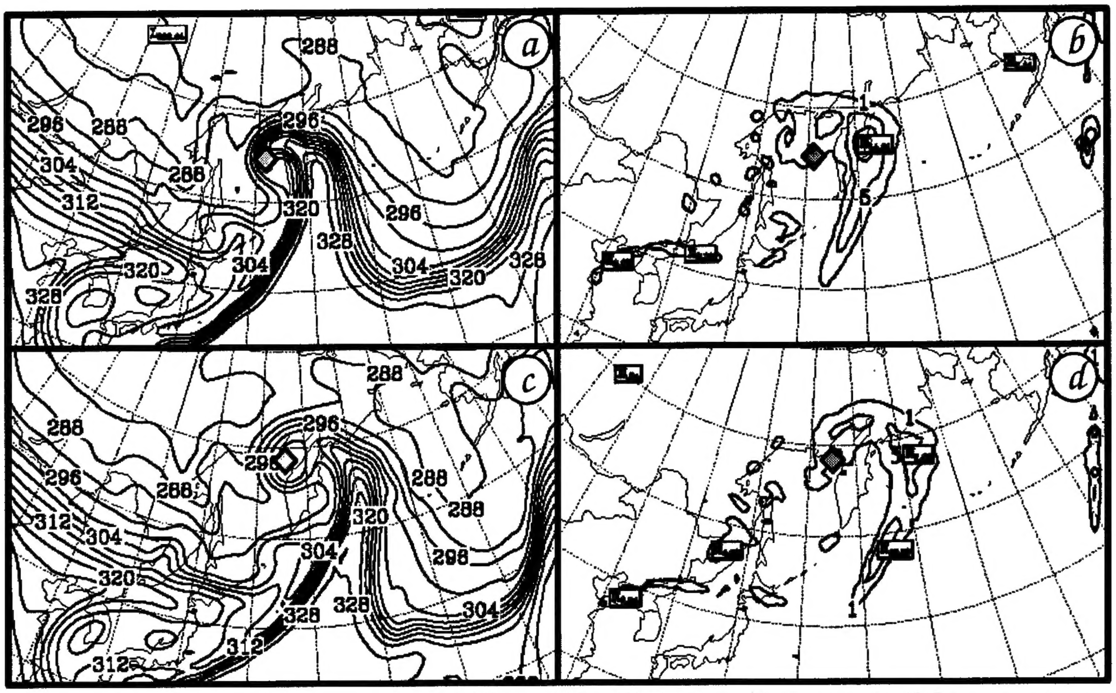

Figure 2. Simulation of a strong trough with predicted 850 mb equivalent potential temperature (contours are 4K) at a) 60 h, and c) 72 h. Panels b) and d) are the 6-h precipitation (mm/6h, with contours of 1, 5, and 10 mm/6h) corresponding to a) and c).

The interactions of a tropical cyclone with each of the three midlatitude circulation patterns were compared with the control simulations to illustrate the contributions to the extratropical transition of the tropical cyclone. Based on the trough-only results, it was anticipated that the strongest extratropical cyclone would develop in the case of the TC interacting with the strong trough, and the weakest extratropical cyclone would develop in the case of the TC interacting with the weak trough. However, in the case of the set of simulations including the TC, the minimum surface pressures were almost identical (967 mb, 965 mb, and 959 mb) regardless of the strength of the upper-level trough although they were deeper than the trough-only cases (Figure 3). The complexity of the resulting cyclogenesis events indicate that the reintensification stage depends on more than just the strength of the midlatitude upper-level trough.

First, the duration of the *transformation stage* of the tropical cyclone (indicated by the weakening stages in Figure 3) was related to the strength of the midlatitude trough prior to the beginning of the re-intensification. That is, the transformation stage lasted longer, and resulted in weaker tropical cyclone remnants for the weak trough case compared with the strong trough case, and the resulting tropical cyclone intensity with the moderate trough was intermediate as

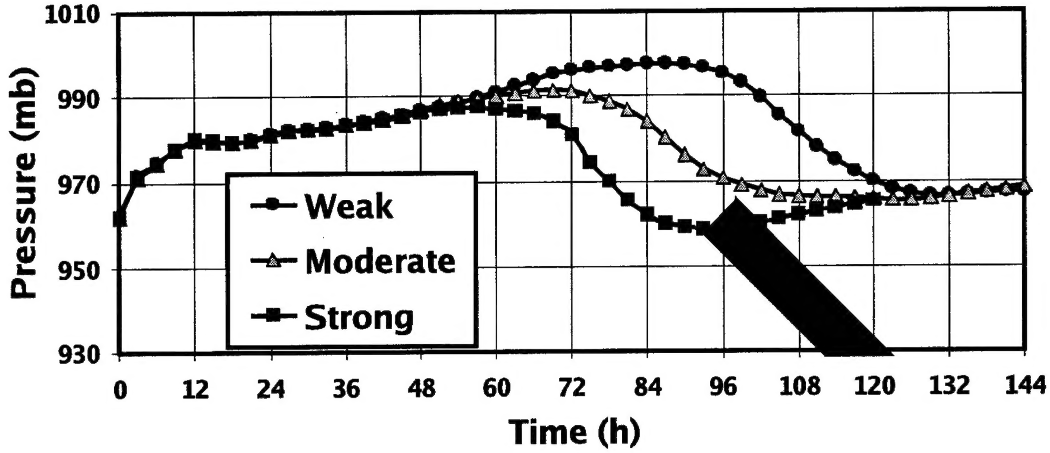

Figure 3. Time series of the minimum surface pressure for each of the three simulations of an interaction between a midlatitude trough and a tropical cyclone.

might be expected. The reason for the weaker (stronger) tropical cyclone at the end of the transformation stage is that a weaker (stronger) northeastward steering flow was associated with the weak (strong) trough environment, which resulted in the TC remaining in the hostile vertical wind shear environment for a longer (shorter) period until a favorable phasing with the midlatitude trough was achieved such that reintensification occurred.

Second, the final intensity of the extratropical cyclone does not appear to be dependent only on the strength of the midlatitude trough. In all three trough-with-TC cases, the final intensities that were achieved were almost identical (967 mb and 27.9 m s^{-1}, 965 mb and 29.4 m s^{-1}, 959 mb and 27 m s^{-1}), especially when compared with the trough-only simulations (1003 mb and 10.9 m s^{-1}, 991 mb and 17 m s^{-1}, and 977 mb and 22.1 m s^{-1}). As has been indicated in previous studies, the critical differences between the strongly reintensifying and weakly re-intensifying storms included the low-level temperature advection, upper-level divergence patterns, and midlevel positive vorticity advection (Peterssen 1956; DiMego and Bosart 1982). In particular, the proper phasing of the tropical cyclone with the midlatitude trough resulted in substantial enhancement of the upper-level divergence (Figure 4) when compared with the trough-only simulations. In addition, higher θ_e values in the lower troposphere associated with the tropical cyclone remnants were absorbed in the developing extratropical cyclone. The lifting of this moist air resulted in precipitation that was greater in both amount and areal extent, which enhanced extratropical development when compared with the control cases (Figure 5). Based on these simulations, an important conclusion is that a weak midlatitude trough interacting with tropical cyclone remnants may have as much potential to intensify, as does a moderate or strong trough, and may have longer periods of rapid intensification.

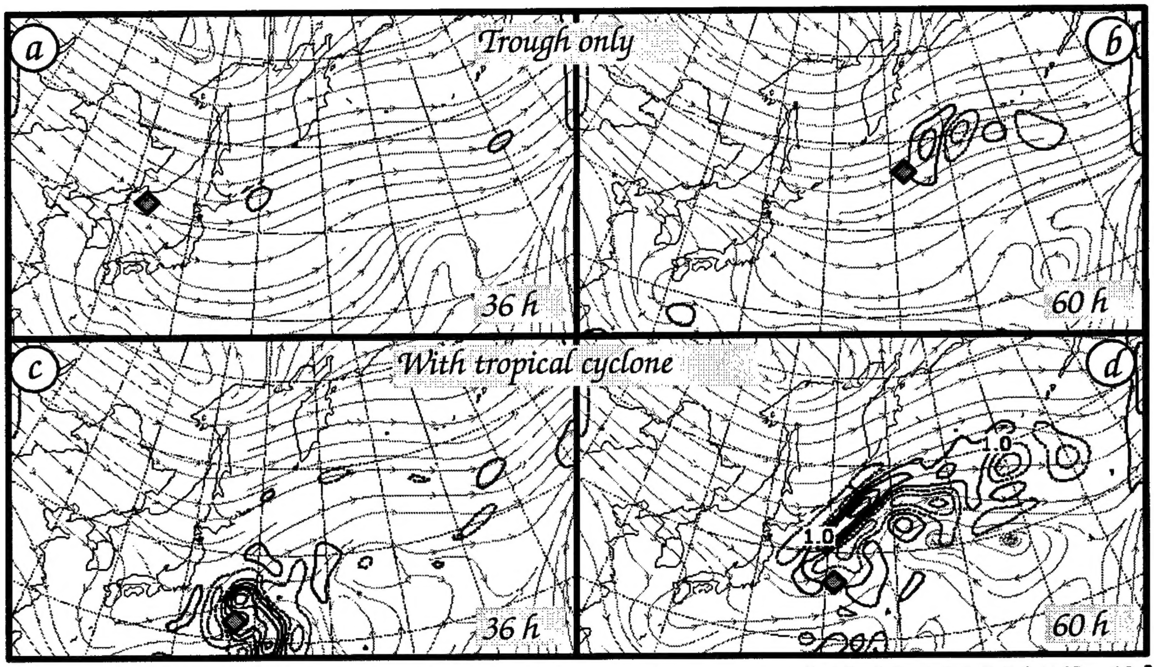

Figure 4. Predicted 250-mb streamlines and divergence (contours are [-5.0,-3.0,-1.0,1.0,3.0,5.0] x 10^{-5} s^{-1}) at a) 36 h, and b) 60 h for the weak midlatitude trough-only simulation. Panels c) and d) are the corresponding fields for the interaction between a tropical cyclone and a weak midlatitude trough.

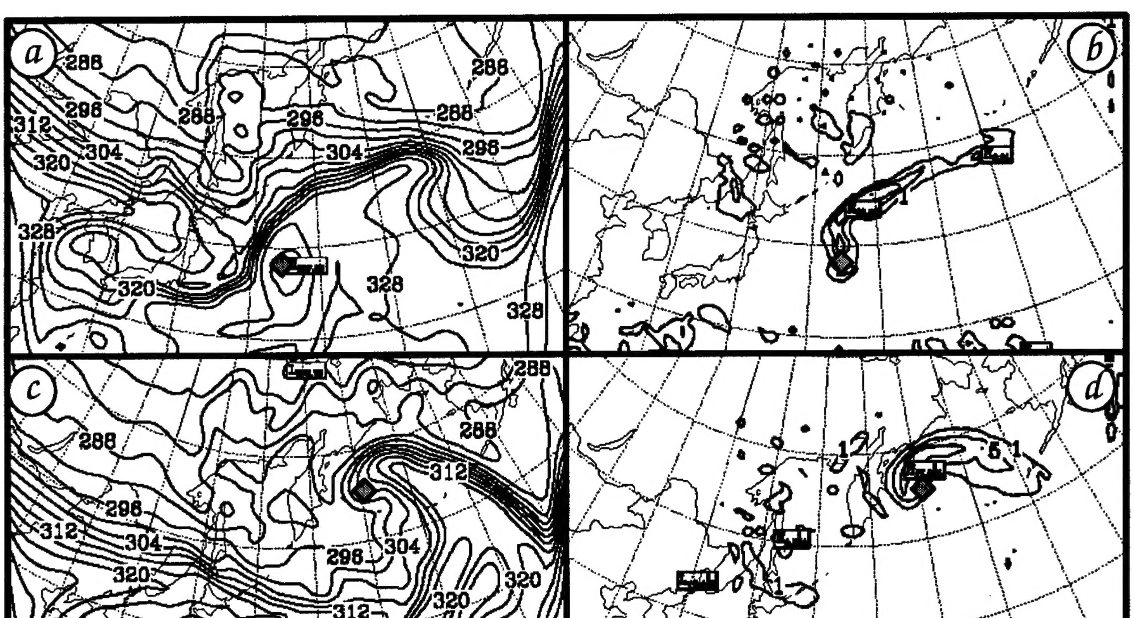

Figure 5. Predicted 850-mb equivalent potential temperatures (contours are 4 K) during the interaction between a tropical cyclone and a weak midlatitude trough at a) 72 h, and c) 120 h. Panels b) and d) are the 6-h precipitation (mm/6h, contours of 1, 5, 10, and 50 mm/6h) corresponding to a) and c).

Summary:

Several advances have been made in the understanding of how a tropical cyclone interacts with the midlatitude environment as it undergoes extratropical transition. In particular, the idea that all things equal, a stronger upper-level trough does not necessarily correlate with deeper intensification is counter-intuitive and is potentially an important result. However, more study is needed to better understand this relationship. The intensity changes associated with extratropical transition of a tropical cyclone are particularly difficult to forecast and the knowledge we gain in studying the physical processes associated with the movement of a tropical cyclone to higher latitudes can help to improve forecasts of these phenomena. Because it is very difficult to get high spatial- and temporal-resolution data sets of extratropical transition, the use of carefully constructed high-resolution simulations is one of our best ways of improving our understanding of the physical processes associated with extratropical transition of tropical cyclones. The work described here will be continued in order to advance this knowledge.

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Publications and Conference Proceedings from this study:

Ritchie, E. A., and R. L. Elsberry, 2003: Simulations of the extratropical transition of tropical cyclones: Contributions by the midlatitude upper-level trough to reintensification. *Mon. Wea. Rev.,* **131,** 2112-2128.

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